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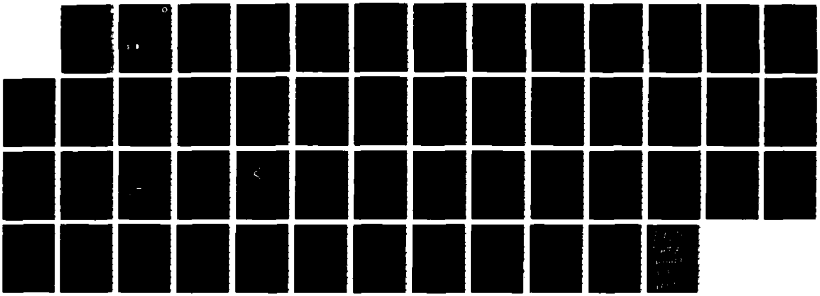

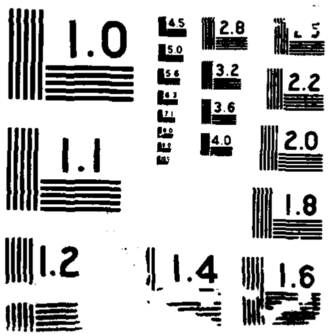
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Guided Radiation Beams in Free Electron Lasers

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In a free electron laser (FEL), the radiation field, wiggler field and electron beam resonantly couple and modify the refractive index in the vicinity of the electron beam, such that the radiation beam will tend to focus upon the electron beam. From the radiation envelope equation derived from the source dependent expansion (SDE) method of solving the 3-D wave equation in FELs, conditions and parameters necessary to achieve guided radiation beams (constant radius) in the Compton exponential gain regime are obtained for FELs driven by either induction linacs or rf linacs with various transverse profiles of the electron beam. From the efficiency of the guided radiation beam, the trapping potential of the ponderomotive potential prior to saturation and the required beam quality of the electron beam can be obtained. The wiggler field could be tapered to further increase the operating efficiency. The possibility of bending or steering radiation beams in FELs is discussed and a condition necessary for radiation guiding along a curved electron beam orbit is obtained. Keywords:

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CONTENTS

GUIDED RADIATION BEAMS IN FREE ELECTRON LASERS

I. Introduction

In many short wavelength free electron laser devices the radiation beam will not be confined or guided by a structure such as a waveguide. Furthermore, in order to provide high gain and efficiency, it is usually necessary for the interaction length (length of wiggler field) to be long compared to the diffraction length (Rayleigh length) associated with the radiation beam. In the FEL the tendency of the radiation beam to diffract away over a distance of a few Rayleigh lengths can be overcome by a focusing phenomenon arising from the resonant coupling of the radiation and wiggler fields with the electron beam.[1,2] This radiation focusing effect plays a central role in the practical utilization of the FEL.[3] This phenomenon was first analyzed for the low gain FEL with transverse effects where it was shown that the diffractive spreading of the radiation beam could be overcome by a focusing effect arising from the modified index of refraction.[1] Experimental evidence indicating optical guiding in the FEL has also been observed recently.[4-7]

Optical guiding in FELs operating in the small signal exponential gain regime has been studied for the asymptotic behavior of the radiation beam,[8-11] indicating that it is possible for the propagation of self-similar transverse modes. Recently, a general formalism for optical focusing, guiding and steering, called the source dependent expansion (SDE) Method, has been developed and applied to FELs.[12] The SDE method is an excellent analytical and numerical technique for solving the wave equation that governs the FEL interaction. An envelope equation for the radiation beam in the FEL can be derived using the SDE method, and it is very appropriate for studying perfect guiding of the radiation beam in FELs operating in the exponential regime. We have obtained analytic expressions

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for the spot size, wavefront curvature, phase shift and growth rate of the perfectly guided radiation beam in FELs operating in the Compton regime for different transverse profiles of the electron beam. The intrinsic efficiency of the FEL in the exponential gain regime with guided radiation can be calculated from these expressions, and from which the trapping potential and desired beam quality at injection can be estimated. It is found that high current rf linacs,[13,14] with their higher energy and better beam quality, are quite suitable for driving relatively short wavelength FELs to beyond saturation where the wiggler is tapered to enhance the efficiency. These results have been verified by simulations based on the SDE method for FELs driven by either induction or rf linacs.

One of the consequences of optical guiding in FEL is the bending of the optical beam by a curved or misaligned electron beam.[17] The SDE formalism allows us to obtain a condition on the curvature of the electron beam in an FEL that the radiation beam will remain guided.

II. Refractive Index Associated with FELs

In our model, the vector potential of an axially symmetric, linearly polarized, radiation field is

$$\underset{\sim}{A}_R(r,z,t) = A(r,z)\ e^{i(\omega z/c-\omega t)}\hat{e}_x/2 + c.c., \tag{1}$$

where A(r,z) is the complex radiation field amplitude, ω is the frequency and c.c. denotes the complex conjugate.

The wave equation governing $\underset{\sim}{A}_R$ is

$$\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \partial^2/\partial z^2 - c^{-2}\partial^2/\partial t^2\right)\underset{\sim}{A}_R = -\frac{4\pi}{c}J_x\hat{e}_x, \tag{2}$$

where J_x (r,z,t) is the driving current density. Substituting Eq. (1) into Eq. (2) leads to the following reduced wave equation,

$$\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + 2i\frac{\omega}{c}\frac{\partial}{\partial z}\right)a(r,z) = S(r,z,a), \tag{3}$$

where $a(r,z) = |e|A/m_0c^2 = |a|\exp(i\phi)$ is the normalized complex radiation amplitude and we have assumed that a(r,z) is a slowly varying function of z, i.e., $|(\partial a/\partial z)/a| \ll \omega/c$. The source function, S, is given by,

$$S = -\frac{4\omega}{c}\int_0^{2\pi/\omega} J_x(r,z,t)e^{-i(\omega z/c-\omega t)}dt. \tag{4}$$

It is possible to relate the source function, S, to the index of refraction associated with the medium by noting that the wave equation for $\underset{\sim}{A}_R$ in a nonmagnetic, time-independent, nonlinear medium is $(\nabla^2 - (n^2(r,z,a)/c^2)\partial^2/\partial t^2)\underset{\sim}{A}_R = 0$, where n is the index of refraction associated with the medium and is, in general, complex and a nonlinear function of a(r,z). Comparing the reduced wave equation written in terms of n(r,z,a) with Eq. (3) we find that the source function can be written in terms of n,

$$S(r,z,a) = (\omega/c)^2\Big(1-n^2(r,z,a)\Big)a(r,z). \qquad (5)$$

The refractive index associated with FELs can be obtained from the following derivation, where a number of simplifying assumptions are made. For example: the beam electrons are monoenergetic without betatron oscillations and that the radiation is of a single frequency.[15] We write the nonlinear driving current density, $\underset{\sim}{J}_x$, as

$$\underset{\sim}{J}_x = -|e|n_b(r)\underset{\sim}{v}_w(z)v_{oz}\int\delta(z-\tilde{z}(t,t_0))dt_0, \qquad (6)$$

where $n_b(r)$ is the ambient beam density, v_{0z} is the axial electron velocity at $z = 0$, t_0 is the time a given electron crosses the $z = 0$ plane, $\underset{\sim}{v}_w(z) = |e|A_w/\gamma m_0 c(\exp(ik_w z) + c.c.)\,\hat{e}_x/2$, is the wiggle velocity, γ is the Lorentz factor, A_w is the vector potential amplitude of the planar wiggler field and $k_w = 2\pi/\lambda_w$ is the wiggler wave number. Substituting Eq. (6) into the expression for S, Eq. (4) gives

$$S = \left(\frac{\omega_b(r)}{c}\right)^2 a_w\int_0^{2\pi/\omega} dt\,\omega/2\pi\int dt_0\, e^{-i\left(\left(\frac{\omega}{c}+k_w\right)z-\omega t\right)}\delta(t-\tau(z_0,t_0))/\gamma, \quad (7)$$

where $a_w = |e|A_w/m_0c^2$, $\tau = t_0 + \int_0^z dz'/v_z(z',t_0)$ and the t_0 integration is over all entry times. Equating Eq. (7) with Eq. (5) and carrying out the integration over t_0, we find the index of refraction associated with the FEL to be given by

$$n_{fel}(r,z,a) = 1 + (\omega_b^2(r)/2\omega^2)\,\frac{a_w}{|a|}\left\langle\frac{e^{-i\psi}}{\gamma}\right\rangle_{\psi_0}, \qquad (8)$$

where $\psi = \int_0^z \Big(\omega/c + k_w - i\ln(a/|a|) - \omega/v_z(z,\psi_0)\Big)dz + \psi_0$ is the relative

phase between the electron and the ponderomotive wave, $\psi_0 = -\omega t_0$ is the initial phase of a given electron and

$\left\langle \right\rangle_{\psi_0} = (2\pi)^{-1} \int_0^{2\pi} d\psi_0$ is an ensemble average over the initial phases. The radial profile of the index of refraction as given by Eq. (8) supports self-focusing of the radiation in an FEL. It should be noted, for completeness, that the relative phase satisfies the pendulum equation given by

$$\partial^2\psi/\partial z^2 = \partial k_w/\partial z - \gamma^{-2}(\omega/c)\left[4^{-1}\partial a_w^2/\partial z - k_w a_w a \sin\psi\right]. \qquad (9)$$

III. Radiation Beam Envelope Equation

In order to solve Eq. (3) we will use the source dependent expansion (SDE) method.[12] This formalism has the merit that with only a few modes it permits an accurate solution of the wave equation throughout the interaction region. In this method, we choose the following representation for a(r,z) in terms of Laguerre-Gaussian functions,

$$a(r,z) = \sum_m a_m(z) L_m\left(\frac{2r^2}{r_s^2(z)}\right) e^{-(1-i\alpha(z))r^2/r_s^2(z)}, \tag{10}$$

where $m = 0,1,2,\cdots$. In Eq. (10), $a_m(z)$ are the complex amplitude coefficients, $r_s(z)$ is the radiation spot size, $\alpha(z)$ is related to the radius of curvature of the radiation beam wavefront, $R = -(\omega/2c)r_s^2/\alpha$ and L_m is the Laguerre polynomial. Solving for the unknown quantities a_m, r_s and α in terms of the source term S allows us to completely describe the radiation dynamics. The representation in Eq. (10) is underspecified, since, when Eq. (10) is substituted into Eq. (3) and moments of the source function taken, there remain more unknown quantities than available equations. The additional degrees of freedom in our representation allow us to specify a particular functional relationship for the unknown quantities r_s and α in such a way that, if the radiation beam profile remains approximately Gaussian, the number of modes needed to accurately describe the radiation beam is small. This yields the following first order coupled differential equations for r_s and α,

$$r_s' - 2c\alpha/\omega r_s = -r_s H_I, \tag{11a}$$

$$\alpha' - 2(1+\alpha^2)c/\omega r_s^2 = 2(H_R - \alpha H_I), \tag{11b}$$

and a set of first order ordinary differential equations for the complex amplitudes $a_m(z)$,

$$a'_m + A_m a_m = -i\left[F_m - mBa_{m-1} - (m+1)B^* a_{m+1}\right], \qquad (11c)$$

where $H = F_1/a_0$, $' \equiv \partial/\partial z$, and $(\ )_{R,I}$ denotes the real and imaginary part of the enclosed function. In Eqs. (11), the functions A_m, B, and F_m are given by

$$A_m(z) = r'_s/r_s + i(2m+1)\left((1+\alpha^2)c/\omega_s^2 - \alpha r'_s/r_s + \alpha'/2\right),$$

$$B(z) = -\left(\alpha r'_s/r_s + (1-\alpha^2)c/\omega r_s^2 - \alpha'/2\right) - i\left(r'_s/r_s - 2\alpha c/\omega r_s^2\right),$$

$$F_m(z) = \frac{c}{2\omega}\int_0^\infty d\zeta\ S(\zeta,z)L_m(\zeta)\exp(-(1+i\alpha)\zeta/2),$$

where $\zeta = 2r^2/r_s^2$.

Equations (11a) and (11b) can be combined to give the following envelope equation for the radiation beam

$$r''_s + K^2 r_s = 0, \qquad (12)$$

where

$$K^2 = (2c/\omega)^2\left(-1 + C^2\langle\sin\psi\rangle^2 + 2C\langle\cos\psi\rangle + (\omega/2c)r_s^2 C'\langle\sin\psi\rangle\right)r_s^{-4}, \qquad (13)$$

$C(z) = (2\nu/\gamma)G(z)a_w/|a_0(z)|$, measures the coupling between the radiation and electron beam, $\nu = (\omega_{b0}\ r_b/2c)^2 = I_b/17\times10^3$ is Budker's constant, I_b is the electron beam current in amperes, $G(z) = (1-f)/(1+f)^2$ and $f(z) = (r_b/r_s)^2$ is the filling factor associated with a Gaussian electron beam density profile. The first term on the right-hand side of Eq. (13) is the usual diffraction term, the second and third terms are focusing while the last term provides a focusing or defocusing contribution. In the high gain

trapped particle regime, $\langle \sin\psi \rangle$ and $\langle \cos\psi \rangle$ are approximately constant, while $|a_0(z)|$ increases with z. Hence, K depends on z and a guided beam ($r_s' = 0$) cannot be exactly maintained in this regime, although the radiation envelope is still reasonably well-confined. In the low gain trapped particle regime $|a_0(z)|$ increases slightly and, therefore, a guided beam can be approximately achieved. In the Compton exponential gain regime, we can obtain the necessary conditions to achieve stable guided radiation beams.

IV. Guided Radiation Beams in the Exponential Gain Regime

By considering the lowest order transverse mode (Gaussian profile) of the radiation beam, we find that the source term appropriate for the high gain Compton regime is,

$$S(r,z)=\frac{(\omega_b(r)/c)^2(a_w k_w f_B)^2}{\gamma(1+a_w^2/2)(\Delta k-i\Gamma)^2}\, a(r,z) \quad ; \qquad (14a,b)$$

where Δk and Γ are the wave number shift and growth rate respectively and f_B is the usual difference of Bessel functions due to the linear wiggler. The lowest order mode is taken to have the form

$$a(r,z) = a_0(0)\exp(i\int_0^z(\Delta k-i\Gamma)dz'-(1-i\alpha)r^2/r_s^2). \qquad (15)$$

For the purposes of illustration, we will consider the Compton FEL regime in which the electron beam has a Gaussian density profile, $n_b(r) = n_0\exp(-r^2/r_b^2)$. The conditions for a guided radiation beam require that the waist and curvature of the radiation beam remain constant, ($r_s' = \alpha' = 0$). Setting $r_s' = \alpha'=0$ in Eqs. (11a,b) and solving for Γ, Δk, r_s, and α, (see Appendix), the following results for a guided beam are obtained.

$$\Gamma = (1+\alpha^2)^{-1}(1+2f)^{-1}\Gamma_0, \qquad \Delta k=\alpha\Gamma, \qquad (16a,b)$$

$$r_s = \left(\frac{\gamma}{\nu}\right)^{1/4}\frac{\lambda_w}{2^{7/4}\pi\gamma f_B^{1/2}}\,\frac{(1+a_w^2/2)^{3/4}}{a_w^{1/2}}\,\frac{f^{1/4}(1+2f)^{3/2}}{(1+3f/2)^{3/4}}, \qquad (16c)$$

$$\alpha = (f/(2+3f))^{1/2}, \qquad (16d)$$

where $\Gamma_0=2f_B(\nu/\gamma)^{1/2}a_w k_w(1+a_w^2/2)^{-1/2}$ and $f=r_b^2/r_s^2$ is the filling factor. In the special case of f=1,

$$r_s(f=1) = 0.25\ \lambda_w \left(\frac{\gamma}{\nu}\right)^{1/4} \frac{(1+a_w^2/2)^{3/4}}{\gamma f_B^{1/2} a_w^{1/2}} .$$

Similar procedures can be performed for other transverse profiles of the electron beam. Conditions for guided radiation beams in the Compton regime for Gaussian, parabolic, and flat-top transverse electron beam profiles are summarized in Table I.

In Fig. 1, we show the spatial evolution of the radiation waist for the induction linac-driven FEL parameters in Table II. The parameters in Table II are consistent with Eqs. (16) and have been chosen to produce a guided radiation beam in the Compton exponential gain regime. The guided beam conditions can be shown to be stable,[16] and Fig. 2 shows that irrespective of the initial value, the spot size asymptotes to the matched (guided) beam value. Figure 3 shows the evolution of the spot size for the rf linac-driven FEL parameters in Table III. As in Table II, the parameters in Table IV have been chosen to produce a guided radiation beam in the Compton exponential gain regime and are consistent with Eqs. (16).

Free electron lasers driven by either induction or rf linacs could initially operate in the guided, exponential gain regime until saturation occurs. Immediately prior to saturation, the ponderomotive potential can be large enough, as in the above illustrations, to trap a significant fraction of the beam electrons. At this point, the wiggler field can be spatially tapered to achieve a significant increase in the operating efficiency and a somewhat smaller input signal into the FEL amplifier.

To determine the viability of tapering the wiggler, prior to saturation, the trapping potential associated with the ponderomotive wave is needed. For linearly polarized waves, the fractional trapping potential is

$$\frac{|e|\phi_{trap}}{\gamma m_0 c^2} = 2\sqrt{2}\left(\frac{aa_w}{1+a_w^2/2}\right)^{1/2} . \tag{17}$$

The radiation amplitude at saturation can be obtained from the intrinsic efficiency of the FEL. Using arguments based on electron trapping in the ponderomotive wave, we find that the intrinsic efficiency in the exponential (maximum) gain regime is

$$\eta = \Delta k/k_w . \tag{18}$$

Using the induction linac parameters in Table II as an illustration, we find that the intrinsic efficiency is $\eta = \Delta k/k_w = 0.66\%$. From this, the fractional trapping potential at the end of the exponential gain regime is $|e|\phi_{trap}/\gamma m_0 c^2 = 6\%$, making it possible to trap the electron beam while tapering the wiggler field. In addition, the initial fractional energy spread of the electron beam must be somewhat less than η. This places a limitation on the fractional energy spread of the electron beam, $\delta E/E_b <$ 0.66%. One contribution to the beam energy spread is the transverse emittance, $\delta E/E_b = (1/2)(\varepsilon_n/r_b)^2$. Therefore, the normalized beam emittance must satisfy, $\varepsilon_n < (2\Delta k/k_w)^{1/2} r_b = 0.034$ cm-rad.

Similar estimates can be carried out for the rf linac parameters in Table III. Even though the intrinsic efficiency is only 0.25%, the fractional trapping potential of 2% prior to saturation is still large enough to trap the electron beam and the wiggler field can be tapered. However, the small intrinsic efficiency puts a more stringent requirement on the beam quality, $\varepsilon < 0.007$ cm-rad, in an rf linac-driven FEL.

Figure 4 shows the relative power for ten transverse modes used in a simulation of the guided radiation beam for parameters in Table II. The fundamental mode is at least three orders of magnitude larger than any of the higher modes, indicating the SDE method is an excellent numerical scheme and the analytic results obtained with only the fundamental mode are well justified.

V. Bending and Guiding of Radiation Beams

Using the SDE formalism, it is possible to discuss the bending of a radiation beam by a curved electron beam in an FEL. For small displacements of the electron beam centroid, a nonaxisymmetric modal expansion similar to Eq. (10) can be performed and the spatial evolution of the centroid of the radiation beam found. Figure 5 shows the centroids of the electron and radiation beams for an FEL in the trapped particle regime with parameters given in Table II. Steering of the radiation beam by the electron beam is clearly demonstrated in this figure.

It is interesting to consider the conditions under which the radiation beam could be guided by a curved electron beam. We denote the radial position by $r = R_0 + x$, where R_0 is the radius of curvature of the electron beam and x is the radial displacement from the center of the curved electron beam, as shown in Fig. 6. The FEL refractive index (correct to order x/R_0) is

$$n = n_{fel} + x/R_0, \tag{19}$$

where n_{fel} is given by Eq. (8) In the exponential gain regime, a guided radiation beam in a curved FEL is possible if $R_0 \gtrsim R_{min}$ where

$$R_{min} = r_s / |\mathrm{Re}(1-n_{fel})|. \tag{20}$$

Substituting the expressions for Γ, Δk and r_s, from Eqs. (16), into (20) yields

$$R_{min} = \frac{4(1+f)f\gamma^2 r_b}{(1+2f)(3f+2)^{1/2} f_B a_w (1+a_w^2/2)^{1/2} (\nu/\gamma)^{1/2}}, \tag{21a}$$

$$R_{min}(f=1) = \frac{1.2\ \gamma^2 r_b}{f_B a_w (1+a_w^2/2)^{1/2} (\nu/\gamma)^{1/2}}. \tag{21b}$$

For a numerical example of R_{min}, consider the following parameters, $\gamma = 100$, $I = 2$ kA, $r_b = 0.3$ cm, $a_w = 1.72$, $f = 1$ and $f_B = 0.85$ (Table II). For these parameters, the minimum turning radius required for a guided radiation beam is $R_{min} = 455$ m.

VI. Conclusion

The source dependent expansion (SDE) method provides an excellent analytical and numerical technique for studying optical focusing, guiding and steering in FELs. We find that guided radiation beams in the FEL can be achieved in the Compton exponential gain regime but cannot be maintained in the high gain trapped particle (tapered wiggler) regime. Conditions for guided radiation beam with different transverse profiles of the electron beam have been derived in the Compton exponential gain regime of an FEL.

Free electron lasers driven by either induction linacs, such as the ATA, or high current rf linacs can operate in the guided, exponential gain regime until saturation occurs. At this point, the wiggler field could be spatially tapered so as to operate the FEL in the trapped particle regime in order to further increase the operating efficiency.

We also examined the possibility of bending or steering radiation beams in FELs. We found a condition which places a lower limit on the radius of curvation of the electron beam necessary for the radiation to be guided along a curved path.

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Table I

Guided Radiation Beam Conditions for Compton Exponential Gain Regime

ELECTRON BEAM PROFILE	$\frac{r_s^2 k_s \Gamma_0}{2\alpha(1+\alpha^2)}$	α^2	$(1+\alpha^2)\frac{\Gamma}{\Gamma_0}$	$\frac{\Delta k}{\Gamma}$	$\frac{\Gamma_0}{(2k_s k_w \nu/\gamma)^{\frac{1}{2}}}$
Gaussian	$(1+2f)^2$	$\frac{f}{3f+2}$	$\frac{1}{1+2f}$		
Parabolic	$\frac{\sqrt{2}f(e^{-2f}+2f-1)}{\left(1-(1+2f)e^{-2f}\right)^{\frac{3}{2}}}$	$\frac{(f-1)+(1+f)e^{-2f}}{(3f-1)+(1-f)e^{-2f}}$	$\frac{\left(1-(1+2f)e^{-2f}\right)^{\frac{1}{2}}}{\sqrt{2}f}$	α	$\frac{f_B a_w}{\gamma}$
Flat-top	$\frac{1-e^{-2f}}{2fe^{-3f}}$	$\frac{1-(1+2f)e^{-2f}}{3-(3-2f)e^{-2f}}$	e^{-f}		

Table II

Parameters Associated with an Induction Linac-Driven FEL in the Exponential Gain Regime

Electron Beam	
Current	I_b = 2kA, (ν = 0.118)
Energy	E_b = 50 MeV, (γ = 100)
Radius	r_b = 0.3 cm
Emittance	$\varepsilon_n < 34\times10^{-3}$ cm-rad
Wiggler Field	
Wavelength	λ_w = 8 cm
Wiggler Strength	B_w = 2.3 kG (a_w = 1.72)
Radiation Beam	
Wavelength	λ = 10.6 μm
Spot Size (guided beam)	r_s = 0.25 cm, (Z_R = 2 m)
e-folding length	$L_e = 1/\Gamma$ = 94 cm
Intrinsic Efficiency	$\eta = \Delta k/k_w$ = 0.66%
Saturated Power	P_{sat} = 660 MW ($a = 7\times10^{-4}$)
Trapping Potential	$\lvert e\rvert\phi_{trap}/\gamma m_0c^2$ = 6.0%

Table III

Parameters Associated with an RF Linac-Driven FEL in the Exponential Gain Regime

Electron Beam	
Peak Current	$I_b = 500$ A
Energy	$E_b = 150$ MeV
Radius	$r_b = 1$ mm
Emittance	$\varepsilon_n \lesssim 7\mathrm{x}10^{-3}$ cm-rad
Wiggler Field (planar)	
Wavelength	$\lambda_w = 12$ cm
Wiggler Strength	$B_w = 900$ G ($a_w = 1$)
Radiation Beam	
Wavelength	$\lambda = 1\ \mu$m
Spot Size (guided beam)	$r_s(0) = 1.1$ mm ($Z_R = 3.8$ m)
e-folding length	$L_e = 1/\Gamma = 196$ cm
Intrinsic Efficiency	$\eta = \Delta k/k_w = 0.25\%$
Saturated Power	$P_{sat} = 180$ MW ($a = 7.25\mathrm{x}10^{-5}$)
Trapping Potential	$\lvert e\rvert\phi_{trap}/\gamma m_0c^2 = 2\%$

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Appendix

Derivation of the conditions for guided radiation beam in the Compton exponential gain regime is shown in the following. When the transverse radiation beam profile is represented by the fundamental mode, Eq. (15), one can combine Eqs. (11a,b,c) to give the three dimensional dispersion relation for the Compton exponential regime,

$$(\Delta k - i\Gamma) + \frac{2c}{\omega r_s^2}(1 - i\alpha) + (\frac{F_0}{a_0} + \frac{F_1}{a_0}) = 0 , \tag{A1}$$

where F_0, F_1 are the overlap integrals of the source function, Eq. (14a), with the zeroth and first Gaussian-Laguerre modes. It can be shown that for the Compton source term, $F_0=F_1(1+2f)$, where f is the filling factor, r_b^2/r_s^2. The dispersion relation Eq. (A1) is then reduced to

$$(\Delta k - i\Gamma) + \frac{2c}{\omega r_s^2}(1 - i\alpha) + 2\frac{F_1}{a_0}(1 + f) = 0 . \tag{A2}$$

By setting $r_s' = 0$ and $\alpha' = 0$ in Eq. (11a,b) for guided radiation beams, we have,

$$(1- i\alpha)^2 = -(\frac{F_1}{a_0})\frac{\omega r_s^2}{c} . \tag{A3}$$

Evaluating F_1/a_0 and substituting in Eq. (A3) gives the relations between the growth rate Γ, phase shift Δk and wavefront curvature factor α, Eqs. (16a,b). Substituting Eqs. (A3) into Eq. (A2) provides a second set of relations between Γ, Δk, α and the guided radiation beam radius r_s,

$$\Delta k + \frac{2c}{\omega r_s^2}[\alpha^2(1 + f) - f] = 0 \ ,$$

$$\Gamma + \frac{2c\alpha}{\omega r_s^2}(2f - 1) = 0 \ . \tag{A4}$$

Eliminating Δk and Γ from Eqs. (16a,b) and (A4) gives the relations of r_s and α with the filling factor f, Eqs. (16c,d). These algebraic equations can be easily solved numerically for the guided radiation beam values of r_s, α, Δk and Γ.

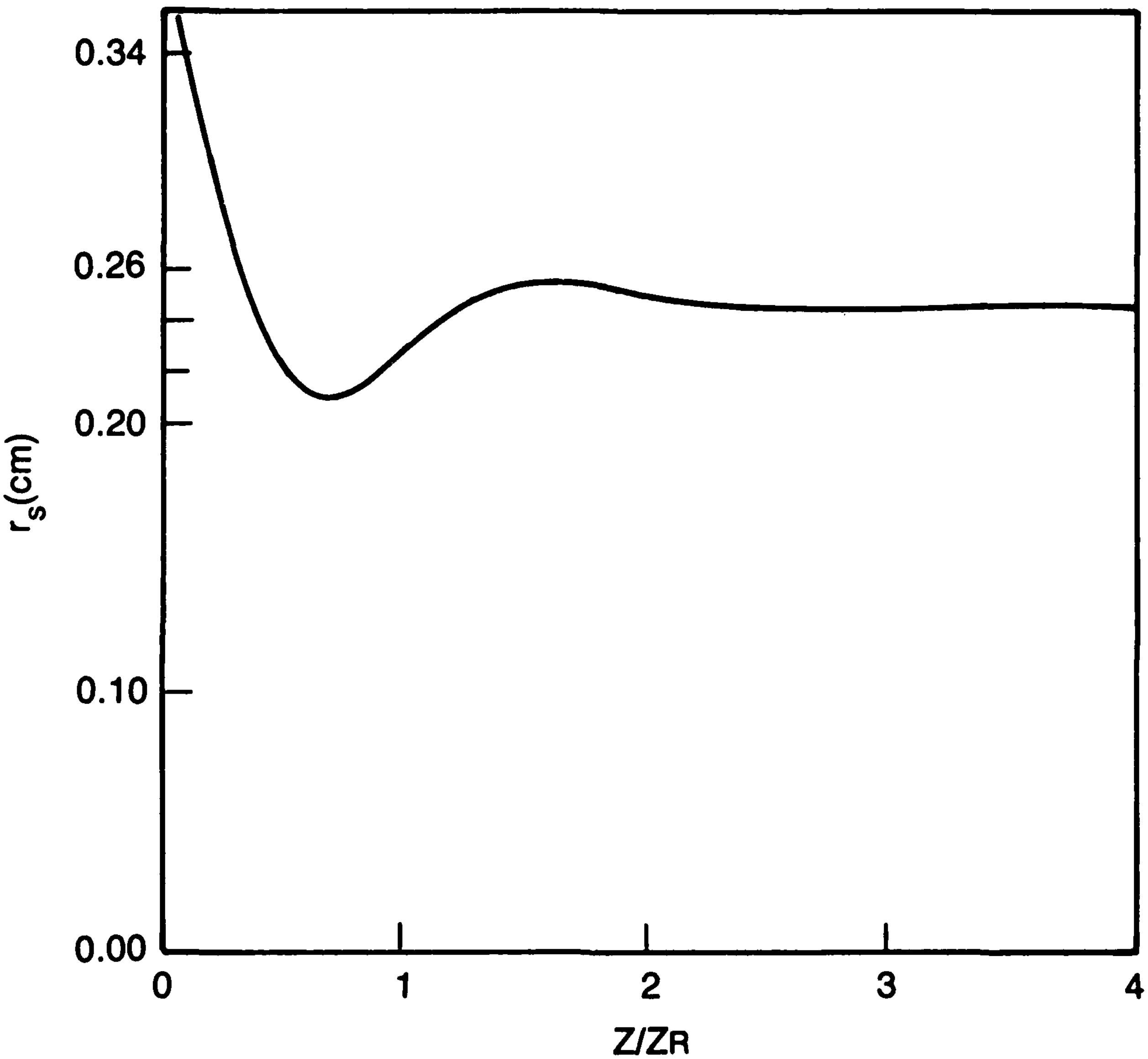

Fig. 1 Spatial evolution of the radiation spot size in the exponential gain regime for induction linac-driven FEL parameters given in Table I.

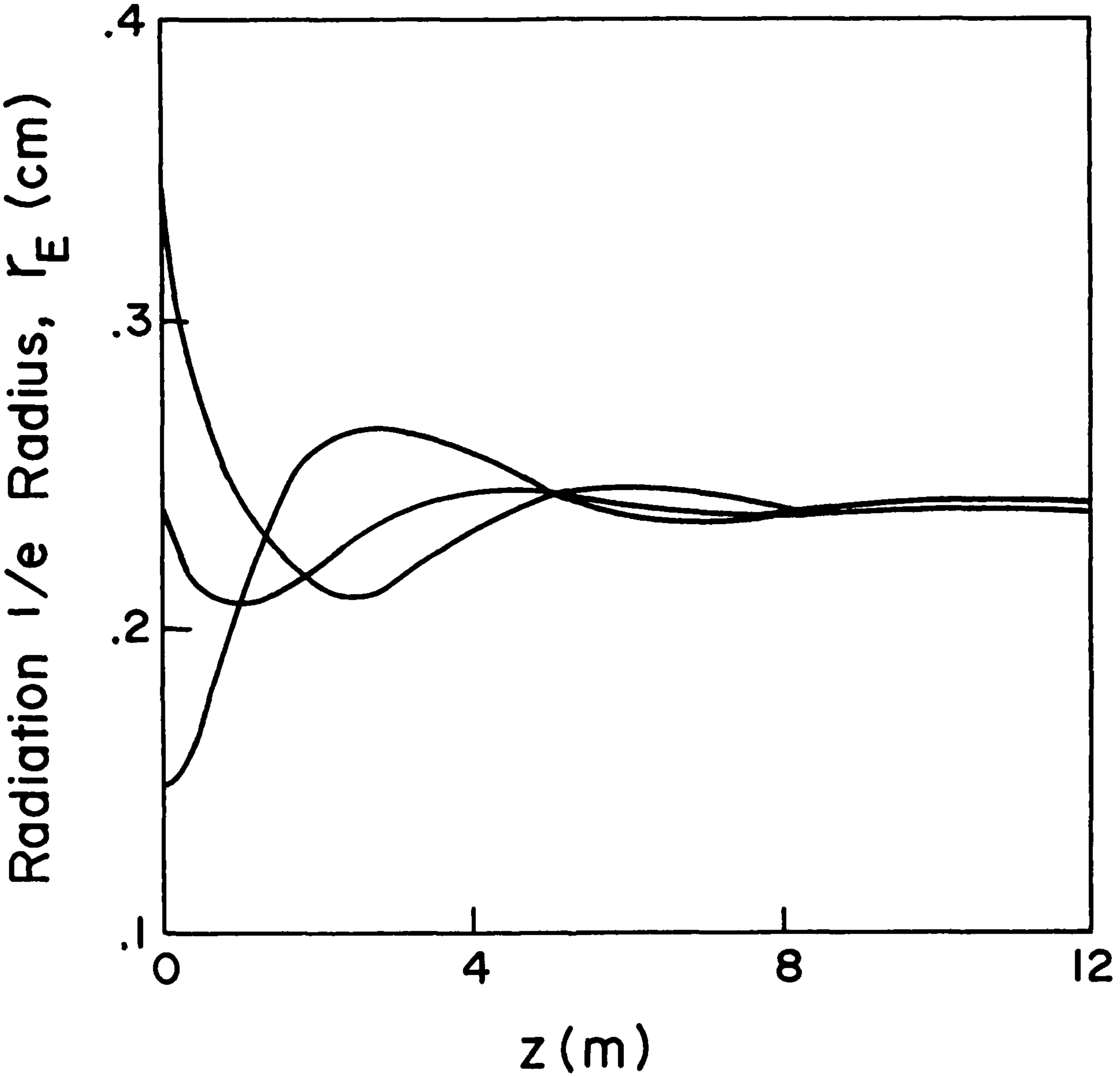

Fig. 2 Spatial evolution of the radiation spot size in the exponential gain regime for initial spot sizes; a) 0.35 cm, b) 0.24 cm, and c) 0.15 cm.

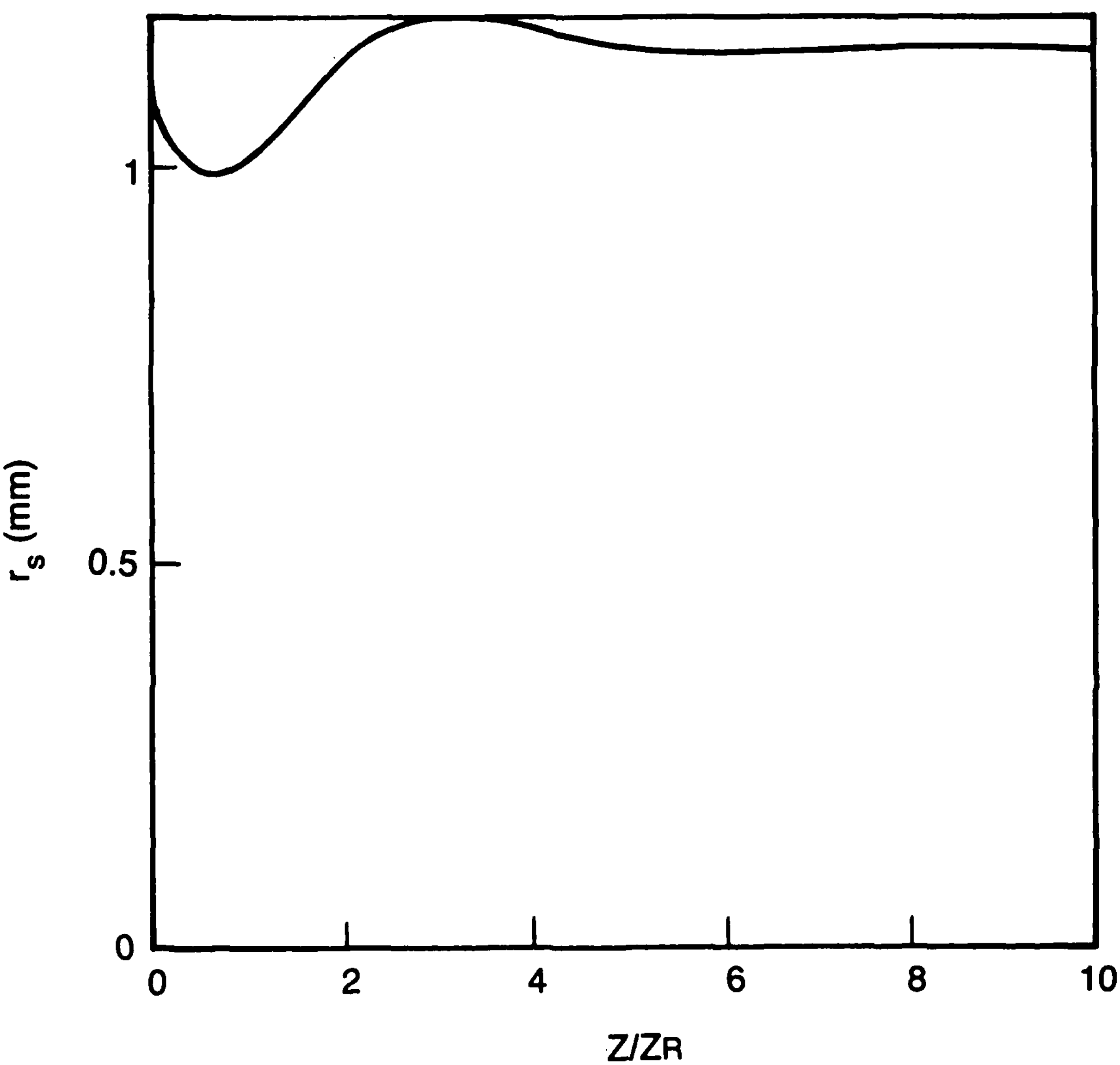

Fig. 3 Spatial evolution of the radiation spot size in the exponential gain regime for rf linac-driven FEL parameters given in Table II.

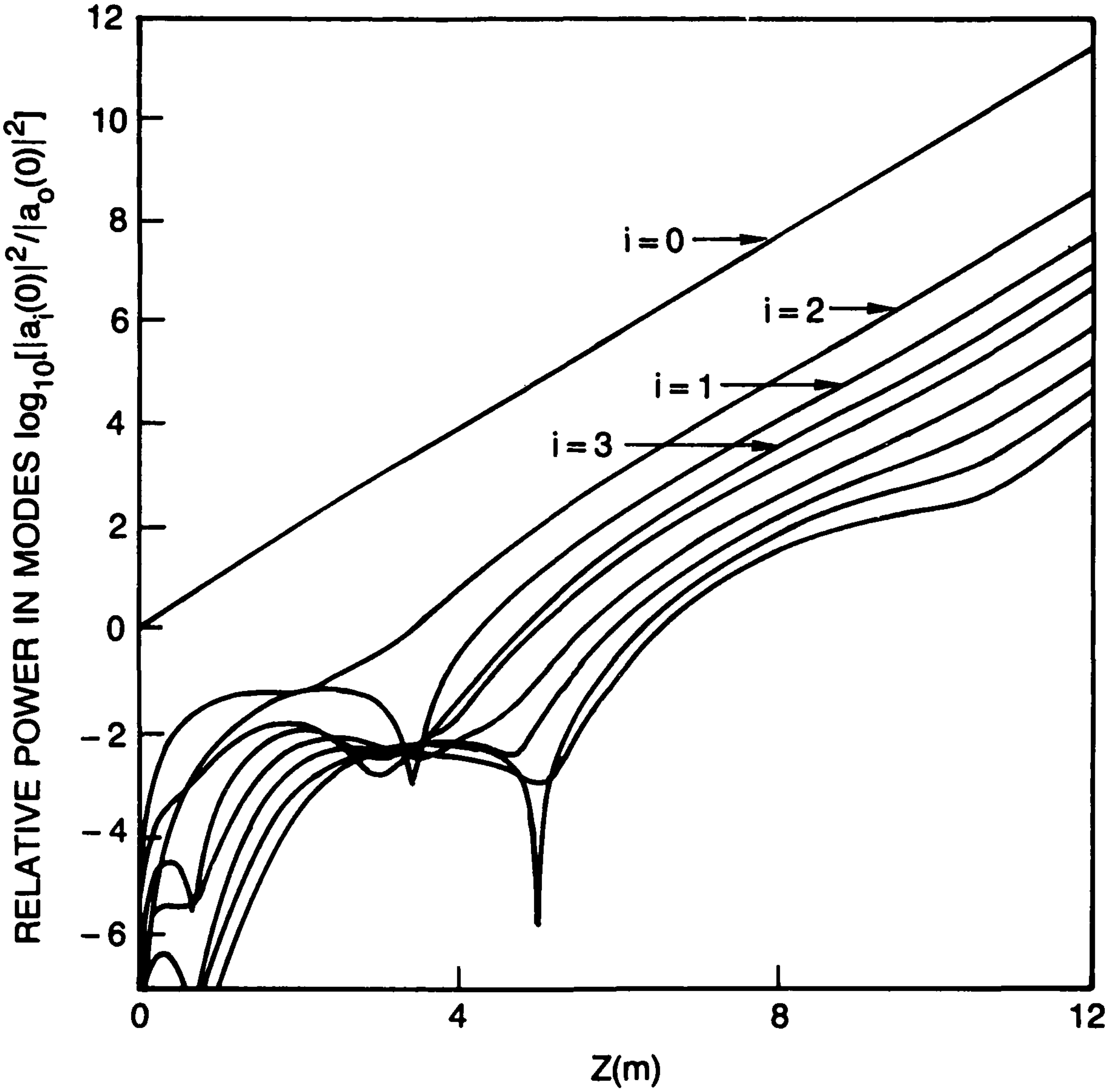

Fig. 4 Spatial evolution of the power in 10 SDE modes, $|a_i(z)|^2/|a_0(0)|^2$, $i=0,..,9$, for FEL parameters given in Table I.

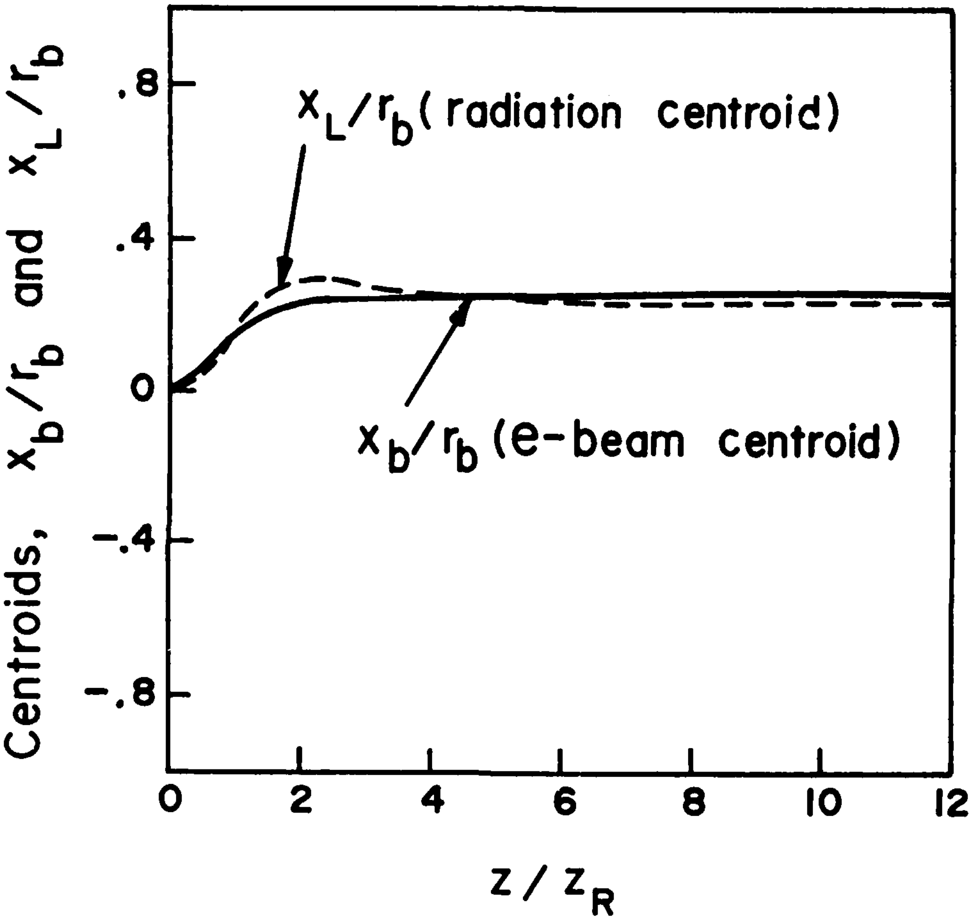

Fig. 5 Electron and radiation beam centroids, x_b and x_L for a displaced electron beam, $x_b = x_c(1-\mathrm{sech}(k_c z))$ with $x_c = r_b/4$ and $\lambda_c = 2\pi/k_c = 4Z_R$.

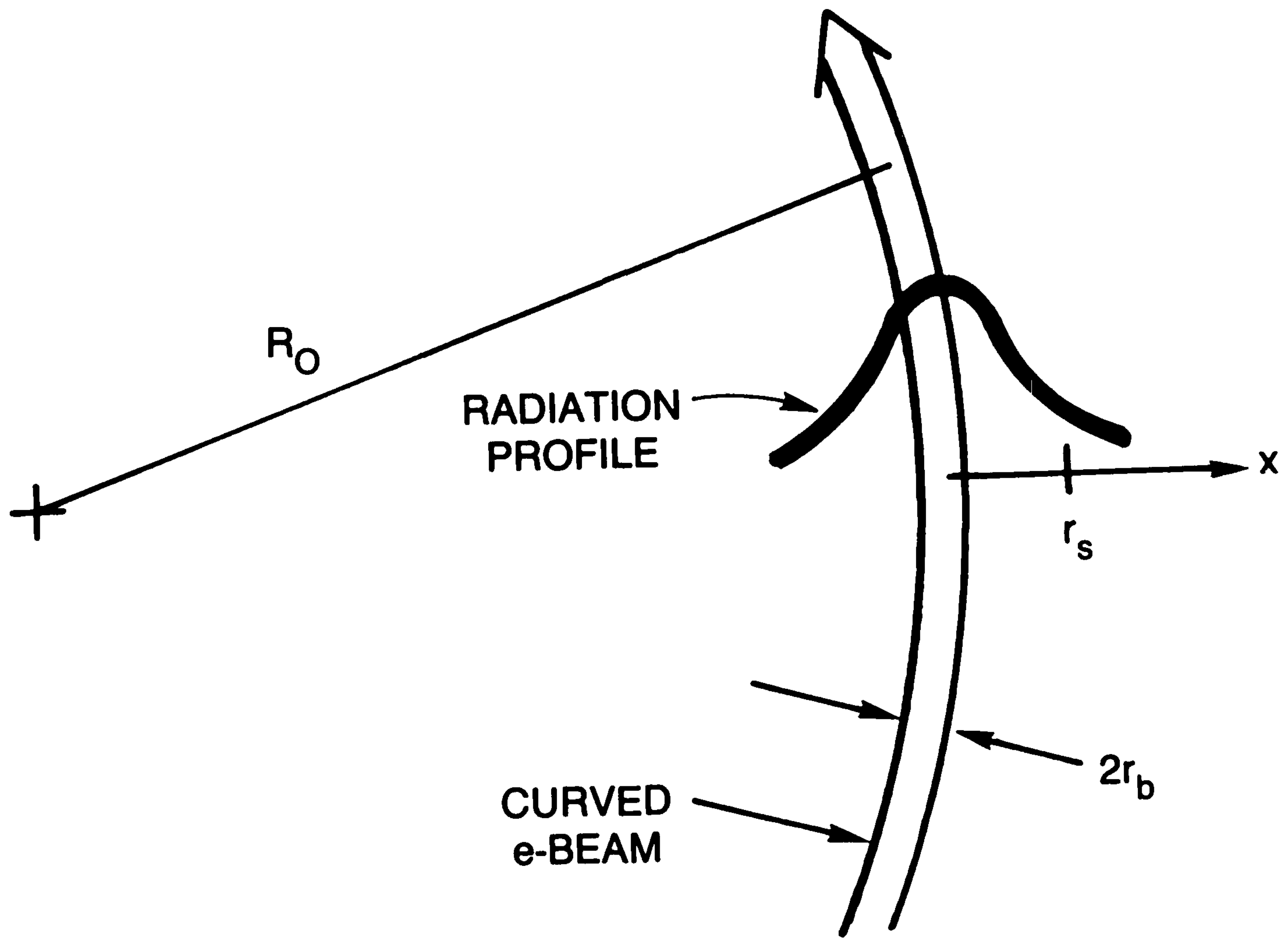

Fig. 6 Configuration showing guiding of radiation beam by a curved electron beam with radius of curvature, R_0.

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